INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2010)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/joc.2186

Trends in column integrated water vapour over Europe from 1973 to 2003

Cristian Mattar,[a]* José A. Sobrino,[a] Yves Julien[a] and Luis Morales[b]
[a] *Global Change Unit, Image Processing Laboratory, University of Valencia P.O. Box 22085, E-46071 Valencia, Spain*
[b] *Environmental Science Department, University of Chile, Av. Santa Rosa 11315, Casilla 1004, Santiago, Chile*

ABSTRACT: The spatial and temporal variations of atmospheric precipitable water (PW) content anomalies were analysed over Europe from 1973 to 2003 using daily data (0000 and 1200 UTC) from National Center of Environmental Prediction and National Center of Atmospheric Research Reanalysis project (NCEP-1) and *in situ* radiosonde data. Mann–Kendall trend tests were applied to long-term PW time series. Technology changes influence PW radiosonde trends, although these are in agreement with NCEP-1 trends. Over the south of the Iberian Peninsula, trends are negative and statistically significant (<-0.04 mm year^{-1}; $p < 0.05$) and positive over the Central European Mountains (The Alpes) and the North Atlantic Ocean (>0.04 mm year^{-1}; $p < 0.05$). Seasonal trends revealed negative and significant trends over the Iberian Peninsula for all seasons (<-0.03 mm year^{-1}; $p < 0.05$). Copyright © 2010 Royal Meteorological Society

KEY WORDS precipitable water; trends; radiosonde; NCEP NCAR Reanalysis; Mann–Kendall test

Received 6 November 2008; Revised 10 May 2010; Accepted 12 May 2010

1. Introduction

Water vapour is by far the most important natural greenhouse gas in the atmosphere. It contributes to about two thirds of the natural greenhouse effect and its temporal and spatial variabilities are larger than other greenhouse gases like CO_2 and CH_4 (Wagner *et al.*, 2006). As regards radiative proportion of greenhouse effect, water vapour (including clouds) is responsible for more than 90% of the total radiation (Zastawny, 2006). Increased water vapour provides the single largest feedback on surface temperature (Hansen *et al.*, 1984). The existence of this water vapour feedback increases the importance of other temperature-dependent feedbacks in the system, while no empirical and model/data comparison evidences a negative water vapour feedback (Held and Soden, 2000). For the aforementioned reason, it is therefore vital to monitor changes in atmospheric water vapour content not only to detect global warming but also to validate the large water vapour feedback seen in climate models (Dai, 2006).

One way to estimate the water vapour in the atmosphere is through radiosondes. The radiosonde network is the source of the longest record of humidity throughout the troposphere, although data are affected by measurement inaccuracies (Ross and Elliot, 1996). Despite the inhomogeneities of radiosonde data (Elliot, 1995; Wang *et al.*, 2002), this technology is useful to estimate humidity-related variables such as mixing ratio or specific humidity. These variables are needed to calculate precipitable water (PW), which is the amount of water in a column of the atmosphere with a unitary basal area.

Many studies evidenced an increase in atmospheric water vapour at different altitudes of atmospheric profile (Gaffen *et al.*, 1992; Gutzler, 1992, 1996; Ross and Elliott, 1996; Zhai and Eskridge, 1997; Ross and Elliot, 2001; Trenberth *et al.*, 2005) and at surface level (Gaffen and Ross, 1999; Kaiser, 2000; Robinson, 2000; Sun *et al.*, 2000; Wang and Gaffen, 2001; Groisman *et al.*, 2004; Dai, 2006; Vincent *et al.*, 2007). This increased amount of water vapour (whether PW or specific humidity) at different atmospheric altitudes shows a climatic variability over different parts of the world and need to be studied in its trend and significance. Recent researches show a strong water vapour feedback over Europe that increases the temperature considerably faster than the northern hemisphere average (Philipona *et al.*, 2005). In Central Europe, temperature rises three times faster than the Northern Hemisphere in the last two decades (Philipona and Dürr, 2004). At surface level, data for 1961–90 show increases in vapour pressure for all seasons, although with low statistical significances (Schönwiese *et al.*, 1994; Schönwiese and Rapp, 1997).

The study presented here uses water vapour integrated column over 64 radiosonde stations in Europe from 1973 to 2003 (Table I) and PW data from the National Center of Environmental Prediction (NCEP) and National Center of Atmospheric Research (NCAR) Reanalysis project (NCEP-1) in the same period. This article is structured as follows: Section 2 presents the data and method used

* Correspondence to: Cristian Mattar, Global Change Unit, Department of Thermodynamics, University of Valencia, Dr Moliner 50, Burjasot, Spain. E-mail: cristian.mattar@uv.es

Table I. List of the radiosonde stations used in this work.

Id	Longitude	Latitude	Station code	Name	Id	Longitude	Latitude	Station code	Name
1	9.6	63.7	1241	Orland	33	13.18	46.03	16044	Udine C.
2	5.66	58.86	1415	Sofia	34	9.28	45.43	16080	Milano L.
3	−1.18	60.13	3005	Lerwick	35	17.95	40.65	16320	Brindisi
4	−6.31	58.21	3026	Stornoway	36	9.06	39.25	16560	Cagliari E.
5	1.68	52.68	3496	Hemsby	37	23.73	37.9	16716	Athina A.
6	−5.32	50.22	3808	Camborne	38	36.3	41.28	17030	Samsun
7	−10.25	51.93	3953	Valentia	39	29.08	40.96	17062	Istambul G.
8	−22.6	63.96	4018	Keflavikurflugvollur	40	32.88	39.95	17130	Ankara C.
9	−6.76	62.01	6011	Thorshavn	41	27.16	38.43	17220	Izmir G.
10	12.53	55.76	6181	Koebenhavn	42	30.55	37.75	17240	Isparta
11	5.18	52.1	6260	De bilt	43	34.65	64.95	22522	Kem'
12	5.4	50.03	6476	St Hubert	44	34.26	61.81	22820	Petrozavodsk
13	6.95	46.81	6610	Payerne	45	38.93	61.5	22845	Kargopol'
14	−4.41	48.45	7110	Brest	46	24.58	59.38	26038	Tallinn
15	2	48.76	7145	Trappes	47	30.7	59.95	26063	St Petersburgo V.
16	6.21	48.68	7180	Essey	48	34.05	57.9	26298	Bologoe
17	−0.68	44.83	7510	Bordeaux M.	49	24.05	56.96	26422	Riga
18	4.4	43.86	7645	Nimes C.	50	30.61	56.35	26477	Velikie
19	8.8	41.91	7761	Ajaccio	51	32.06	54.75	26781	Smolensk
20	−8.41	43.36	8001	La Coruña	52	39.91	59.31	27037	Vologda
21	−3.58	40.5	8221	Mad/Barajas	53	37.95	55.75	27612	Moskva D.
22	9.55	54.53	10035	Schleswig	54	27.03	50.16	33317	Shepetivka
23	6.96	51.4	10410	Essen	55	30.56	50.4	33345	Kyiv
24	7.33	49.7	10618	Idar O.	56	23.95	49.81	33393	L'Viv
25	9.2	48.83	10739	Stuttgart Sch.	57	22.26	48.63	33631	Uzhhorod
26	16.36	48.25	11035	Wien H.	58	25.9	48.36	33658	Chernivtsi
27	14.45	50	11520	Praha L.	59	30.76	46.43	33837	Odesa
28	17.53	54.75	12120	Leba	60	34.13	44.68	33946	Simferopol'
29	20.96	52.4	12374	Legionowo	61	36.16	51.76	34009	Kursk
30	19.18	47.43	12843	Budapest L.	62	39.25	51.65	34122	Voronez
31	26.13	44.5	15420	Bucaresti INMH	63	36.13	49.96	34300	Kharkiv
32	23.38	42.65	15614	Sofia O.	64	39.81	47.25	34731	Rostov ND

to analyse and process the PW data. Sections 3 and 4 show an analysis of long-term and seasonal trends of PW anomalies. Section 5 presents the consistency of the retrieved results and Section 6 provides the conclusions and final remarks.

2. Data source and methods

For this study, we analysed two PW datasets. The first of these datasets provides the spatial distribution of the PW and the second one consists of local and *in situ* measurements. The spatial PW dataset has been compiled through the NCEP-1, which covers about 57 years of different types of meteorological data with global coverage at 17 mandatory atmospheric levels (Kalnay *et al.*, 1996). The NCEP-1 Precipitable Water (NCEP-1 PW) dataset extent ranges from 1 January 1948 to till date. Data are available in various formats, and for this study we used the four-daily PW files. These variables are provided at a $2.5 \times 2.5^{\circ}$ latitude–longitude spatial resolution and are qualified as type B (influenced at 50% by measurements model) (Kalnay *et al.*, 1996). We retrieved PW from 1973 to 2003 for our study area: 25° to 70 °N and 30 °W to 50 °E.

Additionally, daily radiosonde profiles have been downloaded from the database of the Atmospheric Science Department of the Wyoming University (http://weather.uwyo.edu/upperair/sounding.html). This database includes more than 1300 radiosonde stations around the world. In Europe, data from around 140 stations are available.

Radiosonde data files sometime provide PW values with errors (e.g. negative PW). For this reason, stations with valid records were selected, for which the data at 0000 and 1200 UTC were analysed and processed separately. Then, physically inconsistent values were eliminated. The major problem with this database is the insufficient information about radiosonde technology changes or station relocations. This is an important factor when analysing the PW trend because a technology change influences significantly the trend magnitude. For this reason, the stations that presented incomplete records of long-term time series were removed from the analysis. Finally, punctual outliers were removed from the time series of selected stations when their value minus the climatologic mean was greater than 3σ, where σ is the climatologic standard deviation. As a result, final daily time series of PW at 0000 and

1200 UTC includes 64 radiosonde stations in Europe (Table I).

Trend presence in PW anomalies has been tested for both dataset (NCEP-1 and radiosondes), and linear trends were retrieved to quantify their magnitude. To detect the trend, we used a non-parametric Mann–Kendall (MK) test with 95% confidence statistic level (Libiseller and Grimvall, 2002)

$$T = \sum_{j<i} \operatorname{sgn}(Z_i - Z_j) \tag{1}$$

where

$$\operatorname{sgn}(x) = \begin{cases} 1, & \text{if } x > 0 \\ 0, & \text{if } x = 0 \\ -1, & if \ x < 0 \end{cases} \tag{2}$$

If the values of $Z_1, Z_2, \ldots, Z_n$ are randomly ordered, this statistic test has expectation zero and variance:

$$\operatorname{Var}(T) = \left\{ n(n-1)(2n+5) - \sum_{j=1}^{p} t_j(t_j-1)(2t_j+5) \right\} /18 \tag{3}$$

where p is the number of tied groups in the dataset and t_j is the number of data points in the j^{th} tied group. Furthermore, if n is large ($n > 10$), T is approximately normal (Kendall, 1975).

Finally, we analysed the long-term and seasonal trends of NCEP-1 and radiosondes PW. In order to show the influences of the p level in the NCEP-1 PW trend, we calculated the p level value over each seasonal and long-term time series. These p level values were further spatialized as isolines over the anomaly long-term trend.

3. Long-term trends

The long-term retrieval of PW anomalies from NCEP-1 data shows a statistically significant negative trend over the south of the Iberian Peninsula, Central Europe and parts of north of Scandinavian Peninsula at 0000 and 1200 UTC (Figure 1). On the other hand, a statistically significant positive trend is evidenced in the North Atlantic region between Iceland and Great Britain. Parts of the Alpes Mountains show a positive trend, although this trend is not statistically significant (Figure 1). At 0000 UTC, a negative trend is observed in most part of Europe, but this trend is statistically significant only in

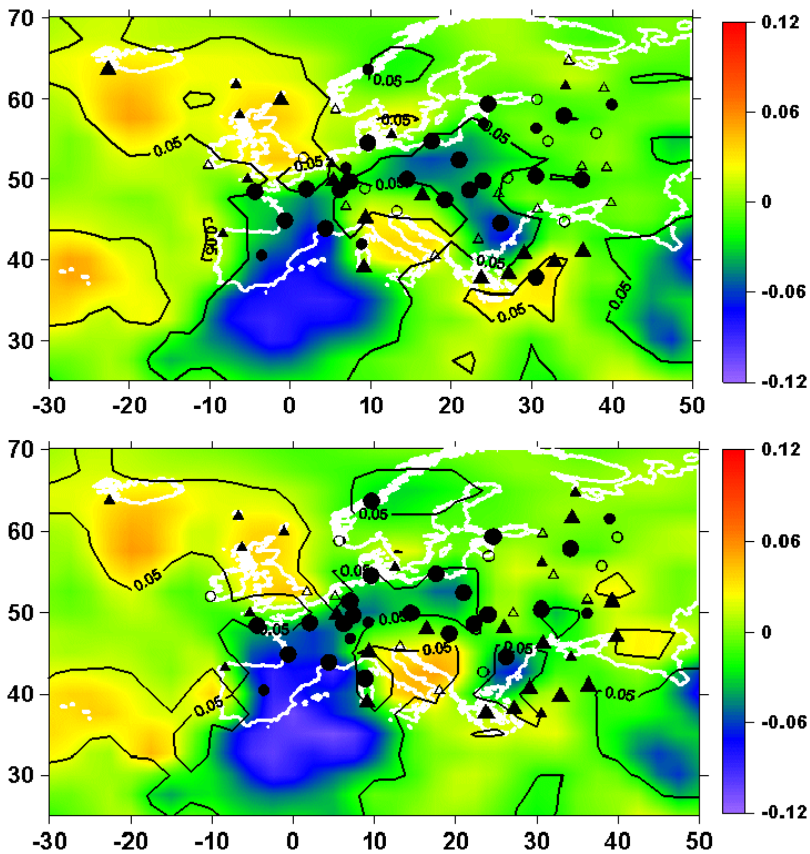


Figure 1. Long-term trends of PW anomalies (mm year^{-1}) at 0000 UTC (top) and 1200 UTC (bottom) for NCEP-1 (spatial data) and radiosonde data (symbols). Positive trends are indicated by triangles and negative trends by circles. Filled symbols indicate that the trends were statistically significant at the 95% level according to Mann–Kendall test. The small symbols indicate trend magnitudes between 0 and 0.04 (mm year^{-1}) and the large symbols denote trend magnitudes greater than 0.04 (mm year^{-1}). The isolines indicate that the trends were statistically significant at 95% confidence level according to Mann–Kendall test for NCEP-1 PW data. These isolines were extracted from a p level image. This figure is available in colour online at www.interscience.wiley.com/ijoc

some areas (south of Iberian Peninsula, France and Eastern Europe). Positive trends with statistical significance are located in Southern Europe (some parts of Mediterranean Sea and Atlantic Sea). Most of Northern Russia has a negative and statistically significant trend.

Radiosonde long-term anomaly trends show similar results to NCEP-1, although some areas exhibit differences in magnitude and significance. At 0000 UTC, Northern Great Britain, Iceland, some parts of Northern Russia and Turkey show a difference in the sign of the trend and its magnitude. At 1200 UTC, these discrepancies between NCEP-1 and radiosonde trends are less pronounced for some areas in Eastern Europe. Most radiosonde stations of Central Europe show negative trends lower than -0.04 mm year^{-1} which are statistically significant. This result is consistent with NCEP-1 trends.

4.. Seasonal trends

We analysed seasonal trends by dividing the time series in four seasons: DJF (December, January and February), MAM (March, April and May), JJA (June, July and August) and SON (September, October and November). In DJF, similar patterns are evidenced at 0000 and 1200 UTC over Iberian Peninsula (Figure 2). A negative and significant trend is observed for Central Europe at both nominal times. The Iberian Peninsula shows a significant and negative trend greater than -0.03 mm year^{-1} at 0000 and 1200 UTC for DJF. Small discrepancies are distinguishable during this season in the Atlantic Ocean: at 0000 UTC the trends are negative over Western Iberian Peninsula and positive in the Northern Atlantic Ocean and south of Azores Islands. However, significant trends are evidenced at 1200 UTC southward of Iceland. The northwest part of Russia shows a negative and non-significant trend in radiosonde data. This situation is different at 1200 UTC with a change in the magnitude and sign of the trend retrieved by radiosonde data. Finally, in the Eastern Mediterranean Sea, a negative and significant trend is retrieved with differences in magnitude between 0000 and 1200 UTC.

There are no significant trends in MAM season at 0000 UTC using NCEP-1 data, except for the North Atlantic and Western Mediterranean Sea. Over the North Atlantic, trends are positive and higher than 0.025 mm year^{-1}, while over Western Mediterranean Sea these are lower than -0.03 mm year^{-1}. The south of the Alpes Mountains shows a positive and significant trend, which is consistent with the radiosonde trends only at 1200 UTC. In most part of Central Europe and Eastern Europe, trends are not statistically significant and do not show a characterizable pattern for this MAM season. At 0000 and 1200 UTC, higher and significant trends are observed in the Western Iberian Peninsula and Northern Great Britain (higher than 0.04 mm year^{-1}). This is in agreement with radiosonde trends in both locations. In the north of Scandinavian Peninsula, a negative and significant trend, lower than -0.025 mm year^{-1}, is observed and confirmed by radiosonde data. In most of Central Europe (CE), no area shows a clearly positive trend whether for NCEP-1 or radiosonde data, except for the south of the Alpes and Italy, where NCEP-1 and radiosonde data show a positive and significant trend greater than 0.03 mm year^{-1}.

For JJA season, at 0000 and 1200 UTC, an important negative trend is observed over Iberian Peninsula and France for NCEP-1 data. Radiosonde trends are localized in Great Britain, and do not present a statistical significance, with the sign of the trend varying with latitude. In contrast with this, the west Scandinavian radiosonde stations show a negative PW trend, although this trend is not statistically significant. On the other hand, Iceland and Northern Great Britain show a positive and significant trend greater than 0.025 mm year^{-1} for 0000 and 1200 UTC, which is confirmed by NCEP-1 and radiosonde data.

Finally, regarding SON season, significant trends retrieved by NCEP-1 and radiosonde data have the lowest spatial extension in comparison with the rest of the analysed seasons. Negative and significant trends are evidenced over the Western Mediterranean Sea, the east of Iberian Peninsula, France, Central Europe and parts of Eastern Europe, at both 0000 and 1200 UTC. Significant and positive trends are evidenced over Iceland, northward of Great Britain and south of Italy. In the rest of Eastern Europe, different results are obtained with radiosondes and NCEP-1 data, although in the central part of Russia a positive and significant trend is evidenced with NCEP-1 but no significant trends are observed with radiosondes over the whole area. At both time measurements the west of the Scandinavian Peninsula shows a negative and significant trend lower than -0.03 mm year^{-1}, which coincides with NCEP-1 PW for 0000 and 1200 UTC. Finally, we observe a positive PW trend with NCEP-1 data at 0000 and 1200 UTC at the south of the Azores Island.

5. Consistency of calculated trends and comparisons

The trends described above show that there is no evidence that PW is increasing over most parts of Central Europe between 1973 and 2003 from NCEP-1 and radiosonde data. This agrees with Trenberth *et al.* (2005), although their study was carried out over a different time period (1988–2001). In fact, we detected negative and significant trends (lower than -0.04 mm year^{-1}) from radiosonde data in the studied period. This result is in concordance with Ross and Elliot (2001), although our results must be analysed with caution due the radiosonde PW processing method which is discussed below. A significant increase of PW is evidenced near the Alpes with radiosonde, while non-significant with NCEP-1 data at both nominal hours (0000 and 1200 UTC). Over the Iberian Peninsula, our results are in agreement with Philipona *et al.* (2005) although with slightly different

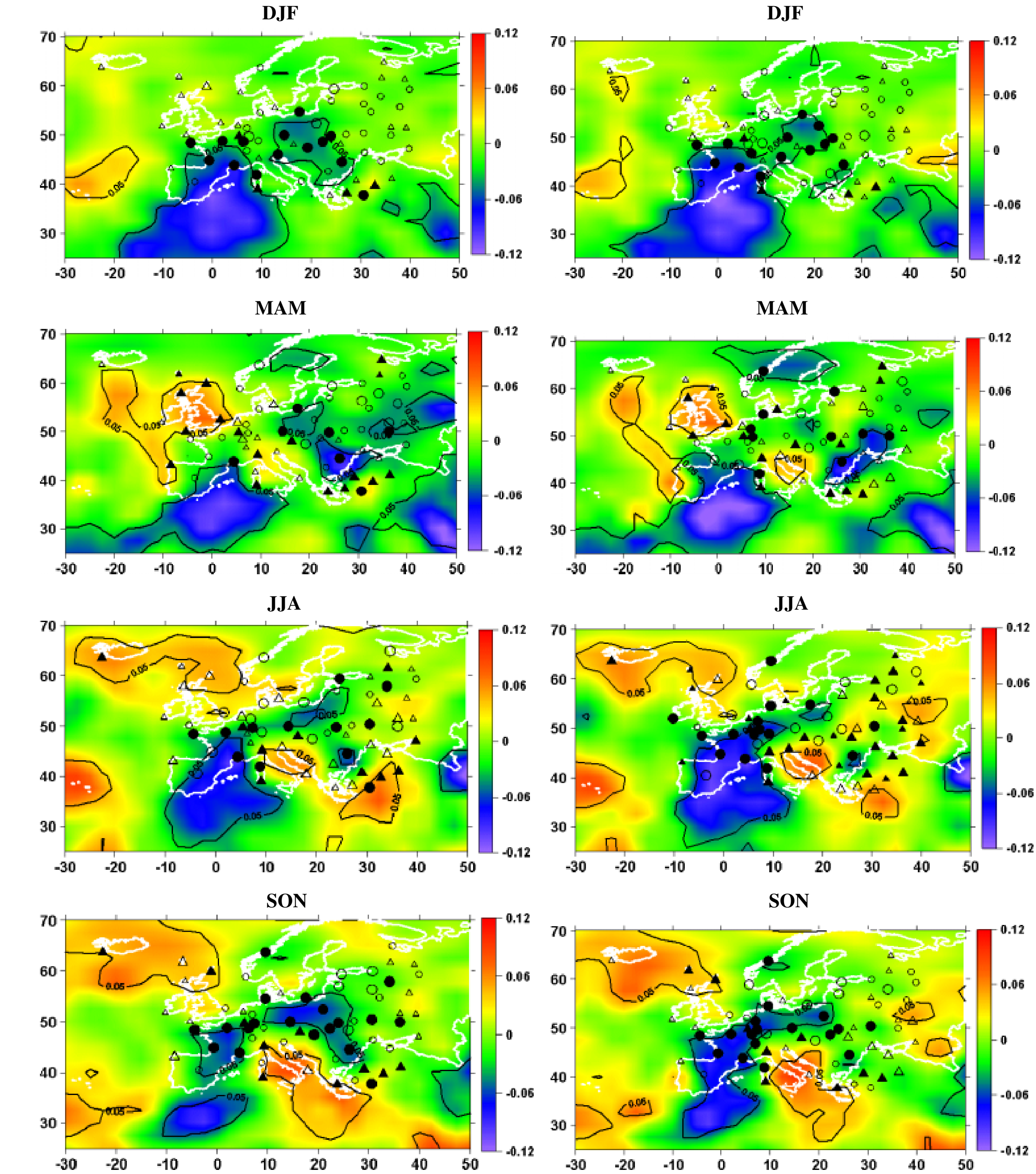


Figure 2. Seasonal long-term mean trends of PW anomalies (mm year^{-1}) for 0000 UTC (left column) and 1200 UTC (right column) for NCEP-1 (spatial data) and radiosonde data (symbols). The description of the symbols and isolines is the same as for figure 1. This figure is available in colour online at www.interscience.wiley.com/ijoc

magnitudes. Another important result is the positive and significant trend in the North Atlantic zone, in opposition to the trends in Central Europe. Similar results over the ocean but for different observation period (from 1988 to 2003) were obtained by Trenberth *et al*. (2005), who also observed a large and positive trend in this area. However, the same author argued that NCEP reanalyses are deficient over the oceans as regards mean, variability and trends. For this reason, it is important to contrast the NCEP-1 PW trends and significances with other sources, like radiosondes. Despite the fact that radiosonde and NCEP-1 PW are not really independent data source, both datasets contribute to analyse the PW trends and its significance.

The radiosonde humidity measurements have been accepted as *in situ* reference standard measurements by the meteorological science community (McMillin *et al*. 2007) despite the important inhomogeneities that this record presents. Karl *et al*. (1995) pointed out that the temporal homogeneity of the data had to be examined before they are used to detect changes in climate. In this work, more than 50% of radiosonde stations were removed from the analysis because they presented strong inhomogenieties in PW record, and we only selected the most regular temporal measurements of the study area. The chosen quality control method is limited because the time of radiosonde technology changes does not appear in the original dataset. This influences our results because in lower troposphere (where the largest amount of water vapour can be found) the measured relative humidity decreased with the switch from VIZ to Vaisala radiosondes (Trenberth *et al*., 2005). A clear example of the effect of technology changes was presented by Ross and Gaffen (1998): a switch in technology changes the magnitude of the measurements and the trend of PW anomaly. On the other hand, more than 51% of the global operating radiosonde stations use Vaisala radiosondes, of which RS-80 models have important dry bias which are well documented in Wang *et al*. (2002), although corrections can be implemented (Miloshevich *et al*., 2001, 2004). In addition, Vaisala instruments are different from the VIZ sensors for temperature and humidity, and furthermore, the signal processing unit of the first instrument was built with short and longwave radiation adjustment, while VIZ observations are not radiation adjusted before transmission over the

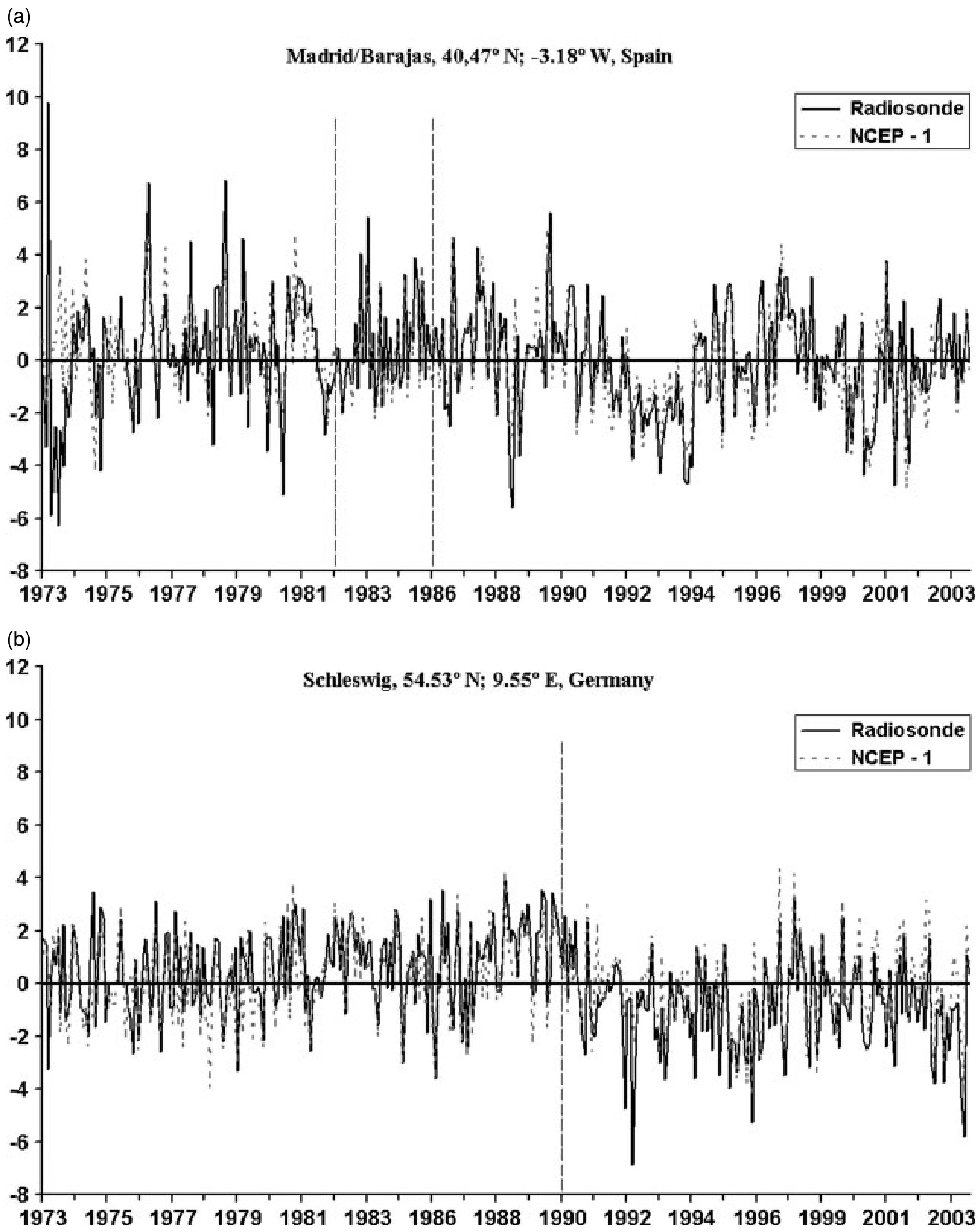
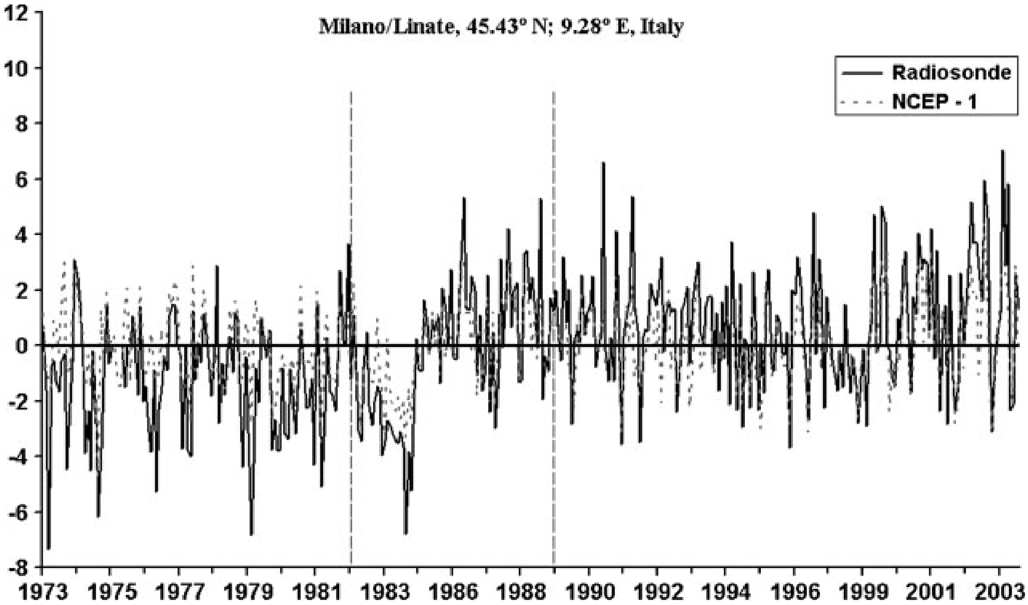


Figure 3. PW anomalies (mm) for different stations in Europe at 1200 UTC such as (a) Madrid, (b) Schleswig, (c) Milano and (d) Praha. Some technology changes are indicated with dashed lines, which respective dates were extracted from Gaffen (1996).

(c)



(d)

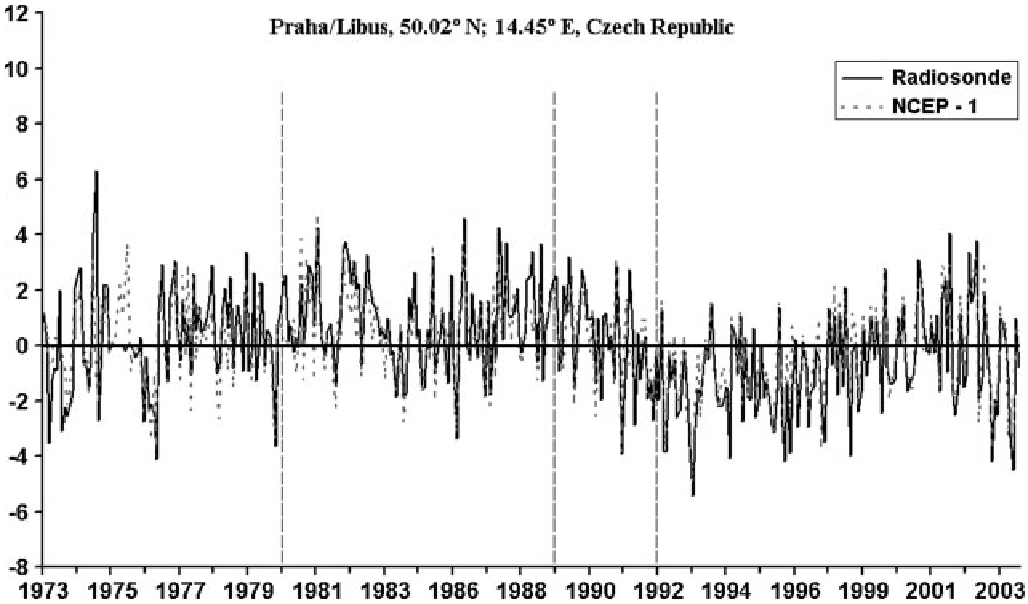


Figure 3. (*Continued*).

global telecommunication system (Elliot *et al*., 2002). The new RS-90 Vaisala technology reduces the error of the RS-80 instrument (Turner *et al*., 2003), but significant calibration issues remain. Therefore, more recent sensor technology is based on the use of a chilled mirror (McMillin *et al*., 2007), although they are used for punctual studies and not for routine observations due the cost of these devices.

However, to correct these anomalies efficiently, one shall determine the specific radiosonde technology for each station and check for these changes. Despite the corrections of technology changes and simple but efficient quality control, we detected important coincidences for PW NCEP-1 trends in some stations and abrupt changes of PW trend due a possible change in technology. Figure 3 presents some PW long-term anomalies retrieved by radiosondes and NCEP-1. However, an important issue is to detect the influence of technology change in the sign or significance of the trend, in this case how a technology change may affect the MK test. For this purpose, four stations have been selected and checked as proposed by Gaffen (1996): Madrid (Iberian Peninsula), Milano (Italian peninsula), Schleswig (Northern Europe) and Praha (Eastern Europe). For Madrid/Barajas (Figure 3a), sonde model changed in 1982 and technology changed from VIZ to Vaisala RS-80 in 1986. The MK test for this station presents a negative and significant trend between 1973 and 2003 lower than -0.04 mm year^{-1}, although the MK test applied for the three periods between radiosonde technology or sonde model changes retrieve a significant and negative trend for the period 1986–2003 for NCEP-1 data. The other periods do not present statistical significance. Another technology change can be evidenced in Schleswig station (Germany) (Figure 3b), where the technology changed from GRAW M60 to Vaisala RS-80, which affects the long-term trend after 1990. Between 1973 and 2003, the trend was negative and significant at 0000 and 1200 UTC (less than -0.04 mm year^{-1}). If we use the MK test before and after 1990, the trend is positive and significant, for radiosonde and NCEP-1 before 1990 and non-significant for radiosonde and NCEP-1 after this date. In Milano/Linate radiosonde station (Figure 3c), two technology changes affect the long-term trend between 1973 and 2003, which presents a positive and significant trend for this period at 0000 and 1200 UTC. Nevertheless, there was a technology change in 1982 from VIZ to Vaisala RS21, while in 1989 a change in sonde model from RS21 to RS80 occurred. The MK test shows a positive and significant trend from 1982 to 1989 while the rest of periods do not present any significance in the MK test. Finally, for Praha/Libus station (Czech Republic) (Figure 3d), two technology and sonde model changes affect PW data in 1980 and 1990. The long-term time series (1973–2003) present a negative and significant trend; however, for the period before 1980 the radiosonde anomaly presents a positive and significant trend, while no significant trend was evidenced afterwards for NCEP-1. The analysis for these four stations shows that the long-term trend may be affected in some cases by technology changes. It is therefore mandatory to compare the trends obtained from radiosonde data with trends obtained from independent data, as has been carried out in this work with NCEP-1 data.

6. Final remarks and conclusions

In this work we analysed PW trends using NCEP-1 and radiosonde data over Europe between 1973 and 2003. A negative and significant long-term mean PW trend was retrieved from both datasets over the Iberian Peninsula, France and Central Europe. Seasonal analysis demonstrated that higher negative trends are obtained for the same areas, which are statistically significant at two nominal hours for all seasons. On the other hand, the Central Alpes, Iceland, the north of Great Britain and Azores Islands present positive and significant PW trend for all seasons and long-term mean trend. These trends can be affected by technology changes or change in sonde model, evidenced in the time series by a strong variation in the PW anomaly, such as a rise or fall in the anomaly values. This was especially the case for radiosonde stations which changed their sonde model to Vaisala instruments.

The radiosonde data files must be corrected from their inhomogeneities or, in its defect, analysed in the period with similar radiosonde technology because technology changes influence the PW trends. The results presented here addressed the PW trends in Europe from radiosonde and NCEP-1 data. These trends would have some relation with the influence of the temperature feedback (Philipona *et al.*, 2005) over Europe, due to the strong relationship which exists between PW and air temperature and their effects in local and global warming.

Acknowledgements

The authors would like to thank the Spanish Ministerio de Ciencia y Tecnología (TERMASAT, project ESP2005-07724-C05-04; EODIX, project AYA2008-0595-C04-01) in addition to the European Union (CEOP-AEGIS, project FP7-ENV-2007-1 proposal No. 212921; WATCH, project 036946) for supporting the work presented in this article. Finally, we also thank the NCEP NCAR Reanalysis project which provided the data by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/.

References

Dai A. 2006. Recent climatology, variability, and trends in global surface humidity. *Journal of Climate* **19**: 3589–3606.
Elliot WP. 1995. On detecting long-term changes in atmospheric moisture. *Climate Change* **31**: 349–367.
Elliot WP, Ross RJ, Blackmore WH. 2002. Recent changes in NWS Upper-Air observations with emphasis on changes from VIZ to Vaisalä radiosondes. *Bulletin of the American Meteorological Society* **83**: 1003–1017.
Gaffen DJ. 1996. A Digitized Medatada Set of Global Upper-Air Stations Histories. NOAA Tech. Memo. ERL ARL-211, 38.
Gaffen DJ, Elliot WP, Robock A. 1992. Relationships between tropospheric water vapor and surface temperature as observed by radiosondes. *Geophysical Research Letters* **19**: 1839–1842.
Gaffen DJ, Ross RJ. 1999. Climatology and trends of U.S. surface humidity and temperature. *Journal of Climate* **12**: 811–282.
Groisman PY, Knight RW, Karl TR, Easterling DR, Sun BM, Lawrimore JH. 2004. Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from in situ observations. *Journal of Hydrometeorology* **5**: 64–85.
Gutzler D. 1992. Climatic variability of temperature and humidity over the tropical western pacific. *Geophysical Research Letters* **19**: 1839–1842.
Gutzler D. 1996. Low-frequency ocean-atmosphere variability across the tropical western Pacific. *Journal of Atmospheric Science* **53**: 2773–2785.
Hansen J, Lacis A, Rind D, Russell G, Stone P, Fung I, Ruedy R, Lemer J. 1984. "Climate Sensitivity: Analysis of Feedback Mechanisms." In *Climate Processes and Climate Sensitivity*. Hansen JE, Takahashi T (eds). American Geophysical Union: Washington, DC; 130–163 pp.
Held A, Soden BJ. 2000. Water vapor feedback and global warming. *Annual Review Energy Environment.* **25**: 441–475.
Kaiser DP. 2000. Decreasing cloudiness over China: an updated analysis examining additional variables. *Geophysical Research Letters* **27**: 2193–2196.
Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* **77**: 437–470.
Karl TR, Derr VE, Easterling DR, Folland CK, Hofmann DJ, Levitus S, Nicholls N, Parker DE, Withee GE. 1995. Critical issues for long-term climate monitoring. *Climatic Change* **31**: 185–221.
Kendall MG. 1975. *Rank Correlation Methods*. Charles Griffin: London.
Libiseller C, Grimvall A. 2002. Performance of partial Mann-Kendall tests for trend detection in the presence of covariates. *Environmetrics* **13**: 71–84.

McMillin LM, Zhao J, Rama Varma Raja M, Gutman SI, Yoe JG. 2007. Radiosonde humidity corrections and potential atmospheric infrared sounder moisture accuracy. *Journal of Geophysical Research* **112**: D13S90, DOI: 10.1029/2005JD006109.

Miloshevich LM, Paukkunen A, Vömel H, Oltmans SJ. 2004. Development and validation of a time-lag correction for Vaisala radiosonde humidity measurements. *Journal of Atmospheric and Oceanic Technology* **21**: 1305–1327.

Miloshevich LM, Vömel H, Paukkunen A, Heymsfeld AJ, Oltmans SJ. 2001. Characterization and correction of relative humidity measurements from Vaisala RS80-A radiosondes at cold temperatures. *Journal of Atmospheric and Oceanic Technology* **18**: 135–156.

Philipona R, Dürr B. 2004. Greenhouse forcing outweighs decreasing solar radiation driving rapid temperature rise over land. *Geophysical Research Letters* **31**: L222, DOI: 10.1029/2004GL020937.

Philipona R, Dürr B, Ohmura A, Ruckstuhl C. 2005. Anthropogenic greenhouse forcing and strong water vapor feedback increase temperature in Europe. *Geophysical Research Letters* **32**: L19809, DOI: 10.1029/2005GL023624.

Robinson PJ. 2000. Temporal trends in United States dew point temperatures. *International Journal of Climate* **20**: 985–1002.

Ross R, Elliott WP. 1996. Tropospheric water vapor climatology and trends over North America: 1973–93. *Journal of Climate* **9**: 3561–3574.

Ross R, Elliot WP. 2001. Radiosonde-based Northern Hemisphere tropospheric water vapor trends. *Journal of Climate* **14**: 1602–1612.

Ross R, Gaffen D. 1998. Comment on "Widespread tropical atmospheric drying from 1979 to 1995" by Schroeder and McGuirk. *Geophysical Research Letters* **25**(23): 4357–4358.

Schönwiese CD, Rapp J. 1997. *Climate Trend Atlas of Europe Based on Observations 1891–1990*. Kluwer Academic Press: Dordrecht, The Netherlands; 228 pp.

Schönwiese CD, Rapp J, Fuchs T, Denchard M. 1994. Observed climate trends in Europe 1891–1990. *Meteorologische Zeitschrift* **3**: 22–28.

Sun B, Groisman PY, Bradley RS, Keimig FT. 2000. Temporal changes in the observed relationship between cloud cover and surface air temperature. *Journal of Climate* **13**: 4341–4357.

Trenberth K, Fasullo J, Smith L. 2005. Trends and variability in column-integrated atmospheric water vapor. *Climate Dynamics* **24**: 741–758.

Turner DD, Lescht BM, Clugh SA, Liljegren JC, Revercomb HE, Tobin DC. 2003. Dry bias variability in Vaisala RS80-Hradiosondes: the ARM experience. *Journal of Atmospheric and Ocean Technology* **20**: 117–132.

Vincent LA, Van Wijngaarden WA, Hopkinson R. 2007. Surface temperature and humidity trends in Canada for 1983–2005. *Journal of Climate* **20**: 5100–5113.

Wagner T, Beirle S, Grzegorski M, Platt U. 2006. Global trends (1996–2003) of total column precipitable water observed by Global Ozone Monitoring Experiment (GOME) on ERS-2 and their relation to near-surface temperature. *Journal of Geophysical Research* **111**: D12102, DOI: 10.1029/2005JD006523.

Wang JXL, Gaffen DJ. 2001. Late-twentieth-century climatology and trends of surface humidity and temperature in China. *Journal of Climate* **14**: 2833–2845.

Wang JH, Cole HL, Carlson DJ, Miler ER, Beierle K, Paukkunen A, Laine TK. 2002. Corrections of humidity measurement errors from the Vaisala RS80–radiosonde – application to TOGA COARE data. *Journal of Atmospheric and Ocean Technology* **19**: 981–1002.

Zastawny A. 2006. Calculation of solar and thermal radiation absorption in the atmosphere, based on the HITRAN data. *Meteorology and Atmospheric Physics* **92**: 153–159.

Zhai P, Eskridge RE. 1997. Atmospheric water vapor over China. *Journal of Climate* **10**: 2643–2652.

